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Modeling of Ultrasonic and Terahertz Radiations in Defective Tiles for Condition Monitoring of Thermal Protection Systems

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Final Report

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Modeling of Ultrasonic and Terahertz Radiations in Defective Tiles for Condition Monitoring of Thermal Protection Systems

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Conclusions from this research activity are summarized as: (1) Cavity like mechanical defects and heat induced damages in porous foam tiles can be detected by electromagnetic THz radiation. (2) Required frequency of the THz beam for sensing mechanical defects depends on the orientation of the defects. THz beam propagating parallel to a cylindrical cavity can detect the cavity at much lower frequency compared to a THz beam propagating perpendicular to the cavity axis. (3) Electromagnetic properties of the foam material are altered significantly, well before its melting point. Therefore, heat induced damage can be easily detected by THz beam, well before the material is melted. (4) Distributed Point Source Method (DPSM) has been extended to model both electromagnetic and elastic wave interaction with defects. DPSM is found to be more efficient than FEM, especially for three-dimensional modeling. (5) Some modifications on the DPSM technique have been suggested to improve the technique's accuracy and efficiency for solving both steady state and transient problems. (6) Some experimental observations have been justified through model predictions.

15. SUBJECT TERMS
Nondestructive Evaluation, THz radiation, Electromagnetic wave, Ultrasonic wave, Distributed Point Source Method (DPSM), Wave Propagation Modeling

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Final Performance Report for Grant Number FA9550-08-1-0318

Title: Modeling of Ultrasonic and Terahertz Radiations in Defective Tiles for Condition Monitoring of Thermal Protection Systems

PI – Tribikram Kundu, Professor, University of Arizona (June 1, 2008 - November 30, 2012)

1. Research Objectives:

Condition based monitoring of Thermal Protection Systems (TPS) are necessary for safe operations of space shuttles in military applications where quick turn-around time is essential. The final objective of this research project was to develop ultrasonic and electromagnetic terahertz radiation (T-Ray) inspection techniques to detect mechanical and thermal damages in TPS tiles.

Ultrasonic waves cannot detect cracks and voids inside the TPS tiles because the tile material (silica foam) has high attenuation for ultrasonic energy; so it does not allow the ultrasonic energy to penetrate deep inside the tiles. Electromagnetic radiation in terahertz frequency range, however, can easily penetrate into the foam material and it has high enough resolution to detect the internal voids. However, this electromagnetic radiation finds it difficult to detect delaminations between the foam tiles and the substrate plate. Thus both these technologies need to be developed for efficient inspection of foam tiles used in TPS.

For understanding the interaction between a defective material and Ultrasonic waves or T-rays, ultrasonic and electromagnetic field modeling in materials with different types of mechanical and thermal damages was also the focus of this research in addition to the experimental investigation. A newly developed semi-analytical technique called Distributed Point Source Method (DPSM) was adopted and improved for this modeling because most other numerical techniques including FEM are not very efficient for high-frequency ultrasonic and electromagnetic terahertz radiation modeling. Some model predictions were verified with experimental results as well.

2. Accomplished Research and its Findings:

2a. Mechanical Damage Detection:

Experiments were first conducted on polymer tiles to see if mechanical damages (such as cylindrical holes) in the tile can be detected by passing THz electromagnetic radiation through it. One can see in Figure 1 that the strength of the transmitted THz beam at frequency 500 GHz and higher was altered due to the presence of a 3 mm diameter cylindrical hole oriented perpendicular to the beam path (left figure) while the same hole when oriented parallel to the beam path (right figure) affected THz beam with frequency as low as 200 GHz [1,2].

A dip near 550 GHz frequency in the transmitted power plot obtained experimentally and shown in the left plot of Figure 2 could be justified from the finite element modeling of the propagated beam (using COMSOL Multi-Physics). Three images shown on the right column of this figure show how the propagated THz beam of frequency 100 GHz (top), 550 GHz (middle) and 1 THz

(bottom) was scattered by a cylindrical hole in a polymer tile on its path. Note that for the 550 GHz signal the beam strength is very low at the midpoint on the right side where the receiver was placed [1, 2].

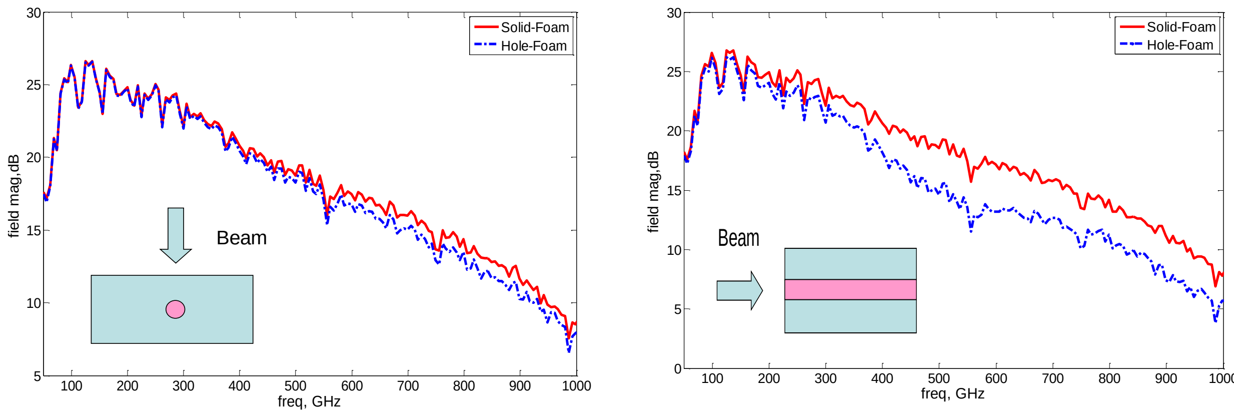

Figure 1: Transmitted THz beam strength as a function of the signal frequency in presence and absence of a cylindrical hole oriented perpendicular (left) and parallel (right) to the beam path [1,2].

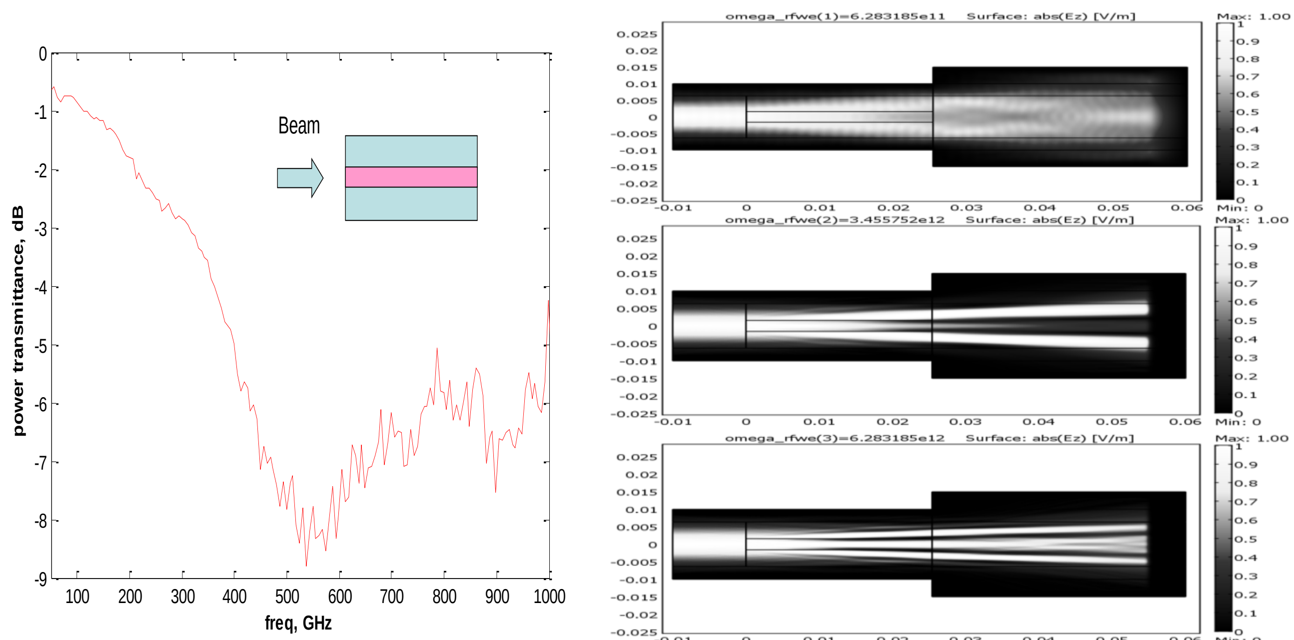

Figure 2: Left plot: experimentally obtained transmitted THz beam power as a function of the signal frequency as the THz beam propagated through a polymer tile containing a cylindrical hole. Finite element model calculations are shown on the right column for 100 GHz (top), 550 GHz (middle) and 1 THz (bottom) frequencies [2].

2b. Heat Induced Damage Detection:

After successfully detecting the mechanical damage, the heat induced damage in porous tiles was inspected by THz beams. Extremely porous artificial pumice stone blocks (see Figure 3) made of polymers were subjected to long term heat exposures at temperatures ranging from room temperature to close to the material's melting point. This kind of polymer is not used as TPS tiles

but it was chosen for this study because like TPS tiles the pumice stone also does not significantly expand or shrink during the heat exposure and it is easily available. It also exhibited some heat induced damage without melting in the oven and was thus an ideal candidate for this study. It was found that effective dielectric properties of porous polymer pumice stones were changed as the heat exposure temperatures were raised. A consistent trend with the heat exposure temperature variation was observed in sub-THz frequency. It was observed (see Figure 3) that the material went through significant changes in its dielectric properties (permittivity index and loss tangent) between 200^{o}C and 400^{o}C, well below its melting point which was near 900^{o}C [1, 3].

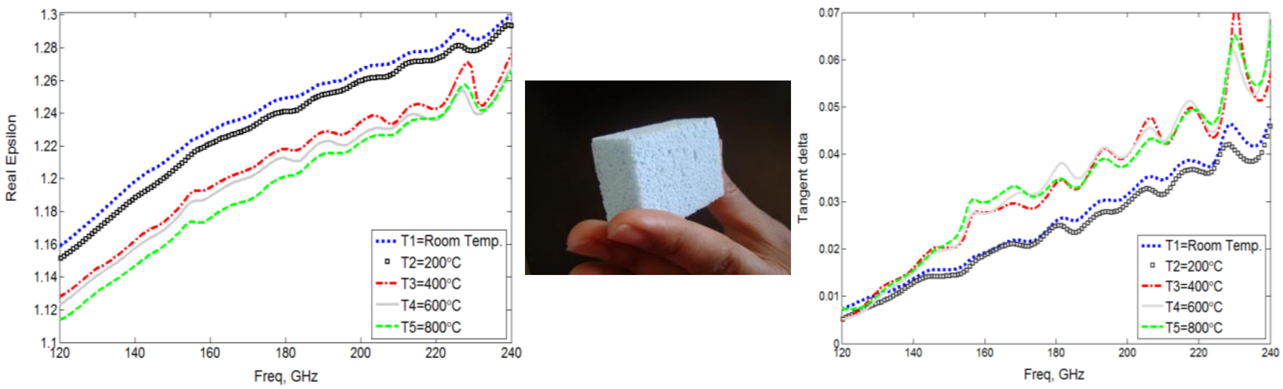

Figure 3: Variations of the electromagnetic properties of a porous tile (which is shown in the middle) as a function of the signal frequency for different heat exposure temperatures – the left figure shows the real part of the permittivity index variation and the right figure shows the loss tangent variations. A noticeable gap can be observed between 200^{o}C and 400^{o}C heat exposure temperatures [3].

2c. Modeling:

Since the three-dimensional modeling of the electromagnetic and elastic wave interaction with scatterers is prohibitively time consuming the distributed point source method (DPSM) was developed for solving the electromagnetic field problems [4] and the DPSM technique was improved further for solving ultrasonic wave scattering problems [5, 6]. The strength distribution for a Gaussian THz beam in front of an emitter is shown on the left image of Figure 4. The other three image of this figure show how the field is affected by single and multiple scatterers.

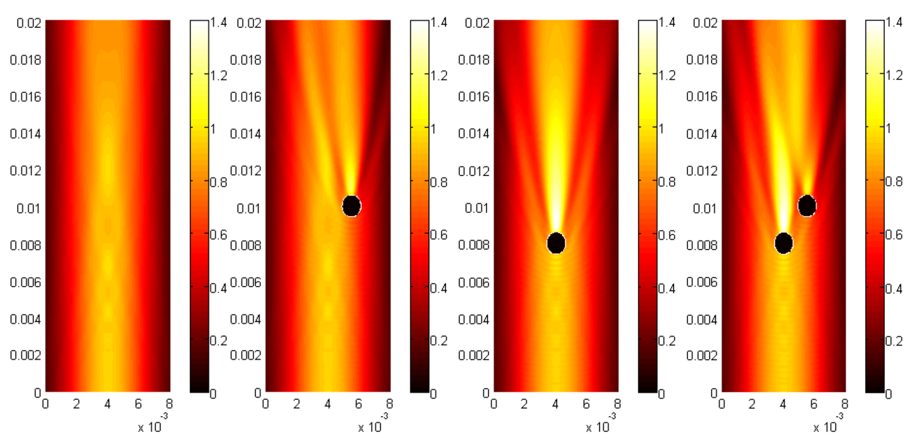

Figure 4: DPSM model generated results for Gaussian THz beam in front of an emitter in absence and presence of dielectric scatterers; left figure - Gaussian Beam with no scatterer; Left-middle figure: Gaussian Beam with an off-axis Scatterer; Right-Middle figure: Gaussian Beam with centrally located single Scatterer, Right Figure: Gaussian Beam with two scatterers [4].

Various improvements on DPSM were carried out to make this technique more accurate and/or efficient, such as G-DPSM and ESM [5] and transient DPSM analysis without going through Fast Fourier Transform [6]. Then this DPSM technique was used to solve different ultrasonic and electromagnetic field modeling problems for NDE (nondestructive evaluation) applications [5-14].

2d. Use of the Acquired Instrument and Knowledge for Solving other NDE Problems:

The instrument and knowledge developed under this research project have been used to solve a number of new NDE problems without compromising the activities of this research project. Those research results have been also published acknowledging the indirect support from the AFOSR [15-17]. The acquired instrument in the NDE laboratory of the University of Arizona will be used for more research related to NDE in the future for which the AFOSR funding will be acknowledged.

2e. List of Publications from this Research Grant

In addition to the book chapter and journal papers [1-17] published from the direct and indirect supports of this research grant a PhD dissertation [18] was completed under this project where the student was supported from this research grant and a number of scientific papers on this research have been presented in the scientific conferences [19-24]. All these publications 1 to 24 are given in the reference list

3. Concluding Remarks and Summary:

Conclusions from this research activity are summarized as:

1) Cavity like mechanical defects and heat induced damages in porous foam tiles can be detected by electromagnetic THz radiation.
2) Required frequency of the THz beam for sensing mechanical defects depends on the orientation of the defects. THz beam propagating parallel to a cylindrical cavity can detect the cavity at much lower frequency compared to a THz beam propagating perpendicular to the cavity axis.
3) Electromagnetic properties of the foam material are altered significantly, well before its melting point. Therefore, heat induced damage can be detected by THz beam well before the material is melted.
4) Distributed Point Source Method (DPSM) has been extended to model both electromagnetic and elastic wave interaction with defects. DPSM is found to be more efficient than FEM, especially for three-dimensional modeling.
5) Some modifications on the DPSM technique have been suggested to improve the technique's accuracy and efficiency for solving both steady state and transient problems.
6) Some experimental observations have been justified by model predictions.

4. Individuals Paid from this Research Grant:

The Principal Investigator T. Kundu and the PhD Students: Mr. Ehsan Kabiri Rahani, Ms. Talieh Hajzargarbashi, Mr. Samik Das, Mr. Umar Amjad and Mr. Cole Branch

References (Publication list from this Research Grant):

Book Chapter:

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